

STELLAR MASS VERSUS STELLAR VELOCITY DISPERSION: WHICH IS BETTER FOR LINKING GALAXIES TO THEIR DARK MATTER HALOS?

CHENG LI¹, LIXIN WANG¹, AND Y. P. JING²*Draft version November 26, 2012*

ABSTRACT

It was recently suggested that, compared to its stellar mass (M_*), the central stellar velocity dispersion (σ_*) of a galaxy might be a better indicator for its host dark matter halo mass. Here we test this hypothesis by estimating the dark matter halo mass for central galaxies in groups as a function of M_* and σ_* . For this we have estimated the redshift-space cross-correlation function (CCF) between the central galaxies at given M_* and σ_* and a reference galaxy sample, from which we determine both the projected CCF, $w_p(r_p)$, and the velocity dispersion profile (VDP). A halo mass is then obtained from the average velocity dispersion within the virial radius. At fixed M_* , we find very weak or no correlation between halo mass and σ_* . In contrast, strong mass dependence is clearly seen even when σ_* is limited to a narrow range. Our results thus firmly demonstrate that the stellar mass of central galaxies is still a good (if not the best) indicator for dark matter halo mass, better than the stellar velocity dispersion. The dependence of galaxy clustering on σ_* at fixed M_* , as recently discovered by Wake et al. (2012), may be attributed to satellite galaxies, for which the tidal stripping occurring within halos has stronger effect on stellar mass than on central stellar velocity dispersion.

Subject headings: dark matter - galaxies: halos - large-scale structure - method: statistical

1. INTRODUCTION

The stellar mass of central galaxies in dark matter halos is believed to be strongly correlated with the dark matter mass of their halos. This relationship has been extensively studied in recent years using a variety of observational probes including galaxy clustering, satellite kinematics, gravitational lensing and group/cluster catalogs. It has also formed the basis for most (if not all) of the current physical/statistical models that aim at populating dark matter halos with galaxies, such as semi-analytic models (SAMs), halo occupation distribution (HOD) models and subhalo abundance matching models (SHAMs). These studies have well established that the stellar mass–halo mass relation for central galaxies can be described by a double power-law form with a relatively small scatter of ~ 0.16 dex (e.g. van den Bosch et al. 2004; Wang et al. 2006, 2007; Yang et al. 2007; More et al. 2009; Yang et al. 2009; Behroozi et al. 2010; Moster et al. 2010; More et al. 2011; Guo et al. 2010; Li et al. 2012; Yang et al. 2012).

Using data from the Sloan Digital Sky Survey (SDSS; York et al. 2000), Wake et al. (2012) recently showed that, when compared to stellar mass (M_*), the central stellar velocity dispersion (σ_*) of galaxies is more closely related to their clustering properties. This led the authors to suggest that σ_* might be better than M_* when indicating the properties of dark matter halos that determine clustering, such as halo mass or assembly history. On the other hand, as the authors pointed out, their finding cannot rule out the possibility that the correlation of dark matter halos with M_* is still tighter than that with

σ_* . It is known that satellite galaxies may well deviate from the stellar mass–halo mass relation of central galaxies, due to the stripping of their outer regions by tidal interactions with their host halos, which has stronger effect on M_* than on σ_* .

This motivates our work, in which we attempt to discriminate between these possibilities by directly measuring the dark matter halo mass for central galaxies of different stellar masses and stellar velocity dispersions. For this we first estimate the cross-correlation function (CCF) in redshift space between a reference sample of galaxies and the central galaxies of groups with given M_* and σ_* . We then estimate the velocity dispersion profile of satellite galaxies around the central galaxies by modelling the redshift distortion in the CCF, from which we determine an average mass for the dark matter halos in which the central galaxies reside. In a recent paper (Li et al. 2012, hereafter Paper I), we have shown that for central galaxies with different luminosities and masses, the dark matter halo masses measured in this way are in good agreement with the results obtained by Mandelbaum et al. (2006) from weak lensing analysis of the SDSS data. When compared to the galaxy–galaxy cross-correlations probed in Wake et al. (2012), the cross-correlation between galaxies and group central galaxies enables us to directly probe the central galaxy – halo mass relation, thus avoiding the effect of satellite galaxies. In addition, the velocity dispersion of satellite galaxies is caused by the local gravitational field, thus is a more direct measure of dark matter halo mass than the clustering amplitude adopted in Wake et al. (2012).

Throughout we assume a Λ cold dark matter cosmology model with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ and $h = 0.7$.

2. DATA AND METHODOLOGY

We apply our analysis to the SDSS galaxy group catalog of Yang et al. (2007). This is a catalog of local galaxy groups with $0.01 < z < 0.2$, and is constructed from

leech@shao.ac.cn

¹ Partner Group of the Max Planck Institute for Astrophysics at the Shanghai Astronomical Observatory and Key Laboratory for Research in Galaxies and Cosmology of Chinese Academy of Sciences, Nandan Road 80, Shanghai 200030, China

² Center for Astronomy and Astrophysics, Shanghai Jiao Tong University, Shanghai 200240, China

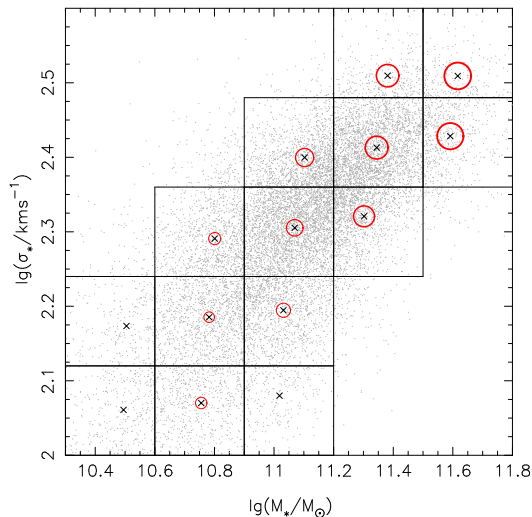


FIG. 1.— Distribution of the central galaxies in the SDSS DR7 galaxy group catalog in the plane of stellar mass (M_*) and stellar velocity dispersion (σ_*). The samples used in this work are indicated by the boxes, with the average M_* and σ_* being marked by a cross in each box. The estimated halo mass for each sample is indicated by the size of the red circles which is scaled by the halo mass.

sample **dr72** of the New York University Value-Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005) using a halo-based group finding algorithm developed in Yang et al. (2005). The stellar mass of each galaxy, M_* , accompanies the NYU-VAGC release, which is estimated by Blanton & Roweis (2007) from the SDSS redshift and photometric data, assuming a universal stellar initial mass function of Chabrier (2003). We use the “total masses” instead of the “Petrosian masses”, obtained by correcting the latter using SDSS “model magnitudes” (see Li & White 2009 and Guo et al. 2010 for details). The central stellar velocity dispersion (σ_*) is available for each galaxy from the SDSS spectroscopy, measured within the $3''$ diameter fiber. We have corrected σ_* to an aperture of one eighth of the galaxy effective radius following Cappellari et al. (2006) and Wake et al. (2012).

As in Paper I, we define the most massive galaxy in each group as its central galaxy. It has been suggested that brightest cluster galaxies (BCGs), or the most massive galaxies adopted here, may be not exactly located at their halo center. However, a recent study by von der Linden et al. (2012) showed that such offsets are small in general; the average offset between X-ray centroids and BCGs are ~ 20 kpc. We use all the central galaxies of which the host groups have three or more member galaxies. This leads to a number of $\sim 16,000$ central galaxies. We divide the central galaxies into 14 samples according to their stellar mass and central velocity dispersion. In Figure 1 we plot the distribution of all the central galaxies in our samples in the plane of M_* and σ_* . The regions of the different samples are indicated by the boxes, while the average mass and velocity dispersion of each sample are marked with a cross. This selection scheme gives us at least two σ_* (M_*) samples at a given M_* (σ_*), enabling us to study the dependence of clustering and halo mass on one of the two parameters while fixing the other. Our samples cover similar M_* and σ_* ranges as those considered in Wake et al. (2012).

For each of the 14 central galaxy samples, we begin by estimating the redshift-space cross-correlation function (CCF), $\xi^{(s)}(r_p, \pi)$, with respect to a reference galaxy sample selected from the NYU-VAGC sample **dr72**. The reference sample consists of about half a million galaxies with r -band apparent magnitudes $r < 17.6$ and absolute magnitudes $-24 < M_{0.1r} < -16$, and redshifts in the range $0.01 < z < 0.2$. Details of the sample selection can be found in Paper I. We then obtain the projected CCF, $w_p(r_p)$, by integrating $\xi^{(s)}(r_p, \pi)$ over the line of sight separation π . Next, we model the real-space CCF $\xi_{cg}(r)$ with a combination of an Navarro et al. (1997) profile and a biased linear autocorrelation of dark matter, and we determine an accurate description of $\xi_{cg}(r)$ by fitting the Abel transform of the model to the observed $w_p(r_p)$. The one-dimensional velocity dispersion profile (VDP) of galaxies around the central galaxies in each sample is then estimated by comparing $\xi^{(s)}(r_p, \pi)$ with $\xi_{cg}(r)$, through modeling the redshift distortion in $\xi^{(s)}(r_p, \pi)$. Finally, we use N -body cosmological simulations to calibrate the relationship between the so-obtained velocity dispersion (VD) and the dark matter halo mass, with which we determine a halo mass for each of our central galaxy sample. Details of our methodology, as well as the reference sample and simulations used for the computation and calibration can be found in Paper I. In this work we estimate errors on all the measurements using the bootstrap resampling technique (Barrow et al. 1984).

3. RESULTS

In Figure 2, we show the projected CCFs determined in the way described above for some of our samples. We plot the results for samples of different σ_* but fixed M_* in the upper panels, and the results for samples of different M_* but fixed σ_* in the lower panels. At fixed stellar mass, the projected CCF shows no or very weak dependence on σ_* , and this is true for all the masses considered ($10.3 < \lg(M_*/M_\odot) < 11.8$) and at all scales probed (~ 15 kpc $< r_p < \sim 30$ Mpc). In contrast, the projected CCF at fixed σ_* shows significant and systematic trends with mass, in both amplitude and slope, and this is true for all the σ_* bins. The CCF amplitude increases with increasing mass at all scales above ~ 100 kpc. This reflects the tight correlation between the stellar mass of the central galaxies and their dark matter halo mass, which clearly holds even when the central stellar velocity dispersion of the galaxies is limited to a narrow range. Moreover, the one-halo term below ~ 1 Mpc shows steeper slopes at lower masses and flatter slopes at higher masses, implying more centrally concentrated distribution of satellite galaxies in less-massive halos (see Paper I for detailed discussion).

In Figure 3, we show the velocity dispersion profile (VDP) of satellite galaxies around our central galaxies, σ_v , measured as a function of the projected separation r_p for different M_* and σ_* samples. Similarly, we see significant mass dependence at fixed σ_* , but very weak or no dependence of the VDP on σ_* at a given mass. We would like to point out two interesting trends that can be read from the lower panels of the figure. First, at scales smaller than ~ 1 Mpc, the velocity dispersion increases with increasing central galaxy mass, with more

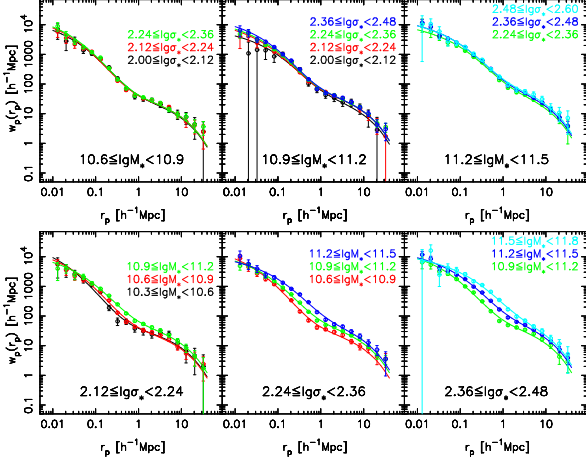


FIG. 2.— The projected cross-correlation function between the central galaxies of groups and the reference galaxies, for central galaxies of different stellar masses (M_*) and stellar velocity dispersions (σ_*), as indicated in each panel. Results from the SDSS DR7 galaxy group catalog are plotted in colorful symbols with error bars, and the solid lines are best-fit models (see the text for details).

remarkable effect at higher masses. The velocity dispersion of galaxies in a group or cluster is caused by the local gravitational field and so, when compared to the large-scale amplitude of CCFs, it provides a more direct and reliable measure of the mass of the host dark matter halo. Thus, the dependence of the small-scale σ_v on M_* at fixed σ_* shows again that the stellar mass of central galaxies is more tightly correlated with halo mass than their central stellar velocity dispersion is. Second, at lower masses ($\lesssim 10^{11} M_\odot$), a mass-dependent shift is seen in the *transition scale* where the velocity dispersion starts to deviate from a flat slope and increase to form a bump at around 1 Mpc. As shown in Paper I (see their fig.4), the transition occurs at around the virial radius of the host dark matter halo. Therefore, the fact that the transition is seen at larger scales for higher stellar masses at fixed σ_* reflects the tight correlation between the central galaxy mass and the virial radius of its host dark matter halo, and thus the halo mass.

We have estimated a halo mass for each central galaxy sample based on a relation between the velocity dispersion measured in our methodology and the dark matter halo mass, as described in § 2. This relation was calibrated in Paper I with the help of a set of high-resolution N -body simulations with the concordance Λ cold dark matter cosmology. In Figure 4, we plot the halo mass estimated in this way as functions of both stellar mass (left panel) and central stellar velocity dispersion (right panel). Results for the samples of different M_* and σ_* are plotted in colorful symbols, with the size of the symbols being scaled by the halo mass. For comparison, we have performed the same analysis for a set of M_* intervals without further dividing the galaxies in each interval into subsamples of σ_* , as well as a set of σ_* intervals without further dividing the galaxies into subsamples of M_* . This gives an *average* relation between halo mass and M_* , and between halo mass and σ_* . The results are plotted as solid triangles connected with solid lines in the figure.

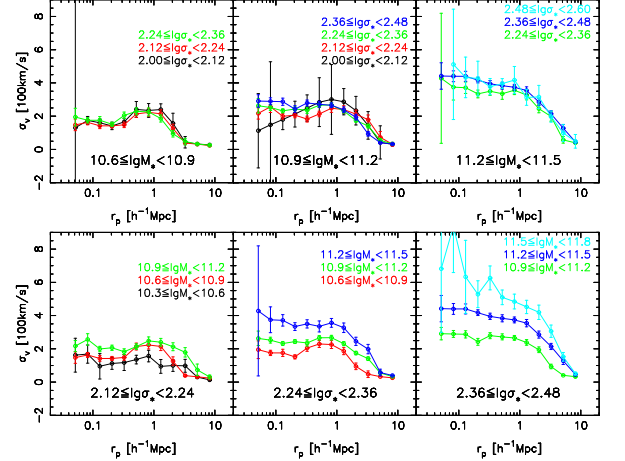


FIG. 3.— Velocity dispersion profile measured for the SDSS DR7 galaxy groups with central galaxies of different stellar masses (M_*) and stellar velocity dispersion (σ_*), as indicated in each panel.

The figure reveals two facts: a) that both M_* and σ_* are correlated with halo mass, and b) that the correlation between M_* and halo mass is much tighter than the correlation between σ_* and halo mass. The rms scatter of the different σ_* samples around the average relation between halo mass and M_* is 15.2% or 0.06 dex, compared to 73.2% or 0.24 dex for the different M_* samples around the average relation between halo mass and σ_* .

We finish this section by highlighting the stronger dependence of halo mass on M_* than on σ_* in Figure 1, where we indicate the halo mass of each sample by the size of a red circle.

4. SUMMARY AND DISCUSSION

Using data from the SDSS DR7, we have derived the velocity dispersion profiles for galaxy groups with central galaxies of different stellar masses (M_*) and stellar velocity dispersions (σ_*). From these we have obtained estimates of the dark matter halo mass for the central galaxies, and investigated the correlation of halo mass for central galaxies with M_* and σ_* . At fixed M_* , we find very weak or no correlation between halo mass and σ_* . In contrast, strong mass dependence is clearly seen even when σ_* is limited to a narrow range.

Wake et al. (2012) recently investigated the cross-correlation functions between galaxies of given M_* and σ_* and the parent sample, finding σ_* to be more closely related than M_* to the large-scale amplitude of the correlation functions. The authors suggested three possible explanations: 1) that halo mass for central galaxies is more closely related to σ_* than to M_* , 2) that halo age (or concentration) for central galaxies is more closely related to σ_* than to M_* , and 3) that halo properties are still more tightly related to M_* than to σ_* and the dependence of clustering on σ_* at fixed M_* are attributed to the contribution of satellite galaxies which deviate from the stellar mass–halo mass relation of centrals.

Our measurements of cross-correlation functions between galaxies and central galaxies and velocity dispersion profiles, as well as the inferred halo masses, are all consistent with the third possibility being the correct, or the most compelling explanation. As discussed in

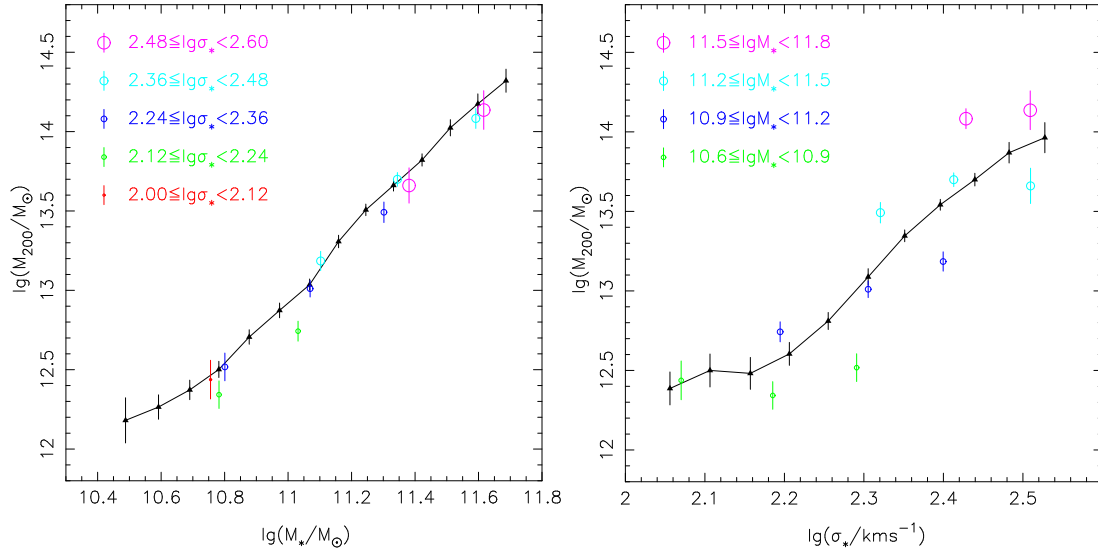


FIG. 4.— Dark matter halo mass as function of galaxy stellar mass (M_* , left-hand panel) and stellar velocity dispersion (σ_* , right-hand panel), measured for the central galaxies of groups in the SDSS DR7. The colorful symbols are for the samples selected on the M_* versus σ_* plane as shown in Figure 1. The solid triangles connected with the line in each panel is for samples selected only by M_* (left panel) or σ_* (right panel).

Wake et al. (2012), tidal stripping may reduce the size and mass of a satellite galaxy as it orbits in its parent halo. This process has stronger effect on stellar mass than on central stellar velocity dispersion, and is stronger in more massive halos. Therefore, at fixed stellar mass, galaxies of higher σ_* are more likely the satellites in higher mass halos, thus clustering more strongly than those of lower σ_* . At fixed σ_* , galaxies of higher M_* are more likely the satellites in lower mass halos, thus lowering down the clustering amplitude and canceling out the mass dependence to some extent.

As can be seen from the right-hand panel of Figure 4, the stellar velocity dispersion of central galaxies is indeed correlated with halo mass, as expected, but with much larger scatter when compared to stellar mass. It is clear that the mass of dark matter halos is correlated more tightly with the stellar mass (M_*) of their central galaxy, than with the central stellar velocity dispersion

(σ_*) of the galaxy. Once the stellar mass is fixed, the central velocity dispersion shows little correlation with halo mass. Our results thus firmly rule out the other two possibilities proposed by Wake et al. (2012).

CL thanks David Wake for helpful discussion, and acknowledges the support of the 100 Talents Program of Chinese Academy of Sciences (CAS), Shanghai Pujiang Programme (no. 11PJ1411600) and the exchange program between Max Planck Society and CAS. This work is sponsored by NSFC (11173045, 11233005, 10878001, 11033006, 11121062) and the CAS/SAFEA International Partnership Program for Creative Research Teams (KJCX2-YW-T23). This work has made use of data from the SDSS and SDSS-II. The SDSS Web Site is <http://www.sdss.org/>.

REFERENCES

- Barrow, J. D., Bhavsar, S. P., & Sonoda, D. H. 1984, *MNRAS*, 210, 19P
- Behroozi, P. S., Conroy, C., & Wechsler, R. H. 2010, *ApJ*, 717, 379
- Blanton, M. R., & Roweis, S. 2007, *AJ*, 133, 734
- Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al. 2005, *AJ*, 129, 2562
- Cappellari, M., Bacon, R., Bureau, M., et al. 2006, *MNRAS*, 366, 1126
- Chabrier, G. 2003, *PASP*, 115, 763
- Guo, Q., White, S., Li, C., & Boylan-Kolchin, M. 2010, *MNRAS*, 404, 1111
- Li, C., Jing, Y. P., Mao, S., et al. 2012, *ApJ*, 758, 50
- Li, C., & White, S. D. M. 2009, *MNRAS*, 398, 2177
- Mandelbaum, R., Seljak, U., Kauffmann, G., Hirata, C. M., & Brinkmann, J. 2006, *MNRAS*, 368, 715
- More, S., van den Bosch, F. C., Cacciato, M., et al. 2009, *MNRAS*, 392, 801
- . 2011, *MNRAS*, 410, 210
- Moster, B. P., Somerville, R. S., Maulbetsch, C., et al. 2010, *ApJ*, 710, 903
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, *ApJ*, 490, 493
- van den Bosch, F. C., Norberg, P., Mo, H. J., & Yang, X. 2004, *MNRAS*, 352, 1302
- von der Linden, A., Allen, M. T., Applegate, D. E., et al. 2012, submitted to *MNRAS*, e-print at arXiv:1208.0597
- Wake, D. A., Franx, M., & van Dokkum, P. G. 2012, submitted to *ApJ*, e-print at arXiv:1201.1913
- Wang, L., Li, C., Kauffmann, G., & De Lucia, G. 2006, *MNRAS*, 371, 537
- . 2007, *MNRAS*, 377, 1419
- Yang, X., Mo, H. J., & van den Bosch, F. C. 2009, *ApJ*, 695, 900
- Yang, X., Mo, H. J., van den Bosch, F. C., & Jing, Y. P. 2005, *MNRAS*, 356, 1293
- Yang, X., Mo, H. J., van den Bosch, F. C., et al. 2007, *ApJ*, 671, 153
- Yang, X., Mo, H. J., van den Bosch, F. C., Zhang, Y., & Han, J. 2012, *ApJ*, 752, 41
- York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, *AJ*, 120, 1579